Corrosion and Deposits in Water-Cooled Generator Stator Windings: Part 2: Detection of Flow Restrictions

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ABSTRACT

Useful methods for detecting flow restrictions in stator bar cooling channels include review of operating parameters and history vs. original design, of generator cooling water chemistry, of strainer and filter clogging history and of results from diagnostic chemical cleaning, as well as monitoring of stator water flow vs. pressure drop, individual stator bar water flow measurements, monitoring of on-line stator temperatures, visual inspections, and DC high-potential (Hipot) testing. A combination of these methods can be selected under consideration of plant specific hardware features and cost-to-benefit relation.

A proactive approach to detecting flow restrictions is recommended in order to permit advanced planning of any needed corrective actions, thus reducing the risk of unplanned maintenance downtime, or even component failure. Managing flow restrictions at an early stage reduces the risk of severe plugging of conductors that may well prove difficult to remove later on.

INTRODUCTION

Flow restrictions in hollow conductors of water-cooled generators are most commonly caused by copper oxide deposits. They may also be caused by various types of debris that have entered the recirculating water, or even by mechanical deformation of the hollow conductors. The resulting load limitations and downtime required for repairs result in serious financial losses. It is therefore useful to have a process that monitors the generator cooling water system for flow restrictions and to have options for removing them.

This article is part of a series of five articles to appear in this journal on corrosion and deposits in water-cooled generator windings [1–5]. This information has also been included in more detail in an Electric Power Research Institute (EPRI) publication [6].

METHODS FOR DETECTING ACTUAL AND POTENTIAL FLOW RESTRICTIONS

Review of Actual Operating Parameters versus Design or Original Equipment Manufacturer (OEM) Recommendations

Such a review may already indicate if a generator is running "as designed" or if it is going its own way. Comparison to sister machines also serves such a purpose, however not even all machines operating in the same plant may perform in a consistent manner. When dissimilar behaviour is found, the reasons and implications should be clarified.

Review of System Operating History

Generally speaking, the generator water cooling system is designed for continuous operation at nominal power. Any other conditions may add an extra influence on the occurrence of flow restrictions, be it for good or for bad.

Stator cooling water temperature Temperature has an influence on the production, migration and deposition of copper oxides. There is strong evidence that hollow conductor plugging becomes more frequent and more intense the higher the temperature is.

The temperatures in the stator windings are determined mainly by generator cooling water inlet temperature, power output and cooling water flow rate. If any of these parameters is changed, attention should be given to a possible impact on deposition in the hollow conductors. Examples are: uprating generator power or changing pump performance.

Make-up water consumption The quantity of make-up water used should be monitored (and recorded) regularly. Any consumption that is more than typical for the system may indicate either a leak or some other type of water loss, e.g. by opening of a component, taking samples etc. For monitoring purposes, an integrating water meter is recommended. A stator cooling system where no water is taken or drained should have a consumption of no more than 20–40 L per year. If the quality of the make-up water is different to that of the system water, it may cause a chemistry transient. The most prominent example is the introduction of aerated make-up water into a low-oxygen cooling water system.

Maintenance and outage lay-up history When the generator is drained by replacing the water with air, the hollow conductors are subjected to a water film with oxygen and carbon-dioxide saturation, that is, some 6–8 $\mathrm{mg \cdot kg^{-1}}$ of oxygen and a pH of ~5.5. This environment is quite different to normal operation and may result in reactions and destabilization within the oxide layer, which may lead to plugging [2].

It is therefore recommended to review each maintenance and lay-up event critically for adverse conditions with regard to hollow conductor performance.

Hydrogen into water leakage history Some hydrogen into water leakage is normal for any generator. Part of it comes through the inherent diffusion of hydrogen through the Teflon™ insulating hoses, another part possibly from leaks through the Teflon-to-metal connections, and possibly also from other pinhole leaks or improperly installed fittings. Depending on the OEM, values of 20–50 L per day are usual and values up to 500 L per day are accepted as normal.

In low-oxygen systems a large amount of hydrogen leakage may introduce oxygen into the stator water system. Depending on the hydrogen purity, more or less oxygen leakage into the system will cause transient oxygen conditions (Figure 1). Even if high-purity hydrogen is used, air will be picked up via the interface with the generator seal oil system and decrease hydrogen purity with time.

In high-oxygen systems large hydrogen leaks may displace the oxygen in the system, thus eventually producing low-oxygen conditions. Such changes in oxidation conditions are detrimental to the stability of the oxide layers and may lead to local re-deposition and flow reductions.

Monitoring hydrogen leakage requires suitable instrumentation. The overall hydrogen consumption of the generator is not conclusive as much larger quantities are consumed by the hydrogen cooling of the rotor-to-stator space. Optimum results are obtained from integrating gas-flow meters at the exhaust of the vent of the generator water cooling system.

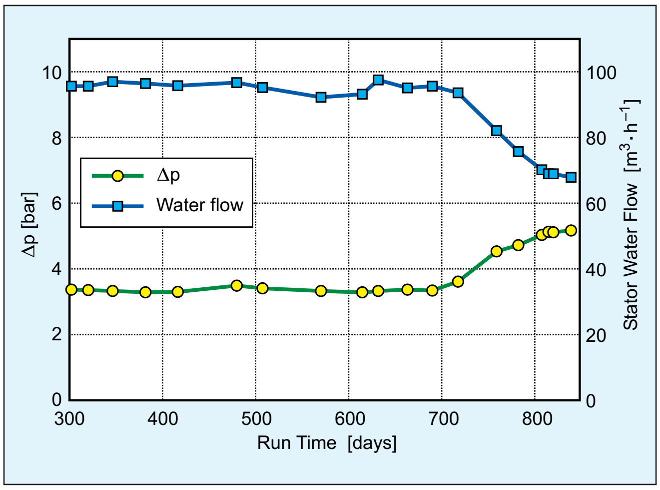

Figure 1:

Plant B2: Long-term trend of stator water flow and pressure drop.

The deterioration of flow and plugging of the generator after day 700 was caused by an ingress of 14 m^3 per day (500 ft^3 per day) of 99.5 % purity hydrogen, originating from a cracked connection tube.

Review of System Water Chemistry

The usual parameters for generator cooling water are conductivity, dissolved oxygen and copper; sometimes pH, electrochemical potential (ECP) as well as possible chemical additives are also monitored [2,7,8]. Monitoring permits comparison of current data to long-term data, to OEM specifications, and to utility and industry experience. Deviations in chemistry may point to the build-up of problems in the generator.

Conductivity While this parameter does not give a direct indication of oxide build-up, it nevertheless identifies the high purity of the water. It should be monitored continuously.

Oxygen Every type of generator water treatment has its own requirements for oxygen. Low-oxygen regimes are usually characterized by $O_2 < 20\ \mathrm{\mu g \cdot kg^{-1}}$, and high-oxygen regimes by $O_2 > 2\ \mathrm{mg \cdot kg^{-1}}$, with the respective values depending on the OEM. Operation outside the oxygen specification brings an increased probability of copper oxide deposits in the system. Therefore monitoring dissolved oxygen in the generator cooling water is important.

Regular analysis at intervals of once per week to once per month is usually adequate if system conditions are stable and the system is tight. In plants equipped with large capacity generators, or where non-continuous monitoring has proven to be difficult and not cost effective, it may be warranted to use on-line monitoring.

For low-oxygen systems, oxygen analysis should be done in such a way that no oxygenated make-up water needs to be added to compensate for sample water loss. For continuous analysis, sample return is indicated. Traditional grab sampling techniques however require substantial amounts of flushing water (2–5 L). If performed frequently, de-oxygenated make-up water should be used.

Copper Of even more importance than oxygen concentration may however be the copper release of the system.

Analyses of grab samples may give a short-term picture, although the low levels make analysis difficult and possibly even unreliable. It is recommended to perform regular copper analyses in the same frequency as non-continuous oxygen analyses.

The copper release of the system is however most reliably measured by integrated sampling with the mixed-bed resin and the mechanical filter [8].

A comparative empirical value may indicate if oxide deposits are less likely to become a problem. We therefore recommend conducting such an analysis on a regular basis and observing the trend. It would also be useful if the OEM, or a user group, were to maintain a comparative database for the specific type of generator. Comparative trending is an important tool for diagnosing "out-of-the-flock" behaviour.

Hydrogen ion concentration (pH) Although this is a relevant parameter, it is not a practical one to monitor regularly. pH measurement in high-purity water is difficult and even unreliable, and may produce erroneous data. Using the correlation of pH and conductivity, conductivity monitoring is a simpler and more reliable substitute [9].

Electrochemical potential (ECP) Measurement of the ECP is a useful indicator for monitoring the copper oxide evolution in the system [8,10,11]. Here again, comparison of data within a user group is beneficial.

Strainer and Filter Clogging

The mechanical filters and/or the strainers collect particles from the water. Over time, the quantity of these particles collected provides a relative indication of oxide transport in the system, which can be a symptom of upcoming flow restrictions in the generator. It is recommended to record any events on the mechanical filters and strainers, e.g. the quantities of oxide removed per period of time, frequency of change of filter elements etc. If an abnormal situation develops, it is useful to check other parameters relevant for detecting any deterioration in generator cooling.

Diagnostic Cleaning

There is one good way to determine the quantity of oxides that are present in the generator, i.e. removal of the oxides by chemical cleaning followed by a determination of their quantity. (This of course requires a cleaning method which dissolves only the oxides, but not the base copper itself, [4].) The quantity and type of matter removed by such diagnostic cleaning gives an indication of the effectiveness of previous system operating practice.

There is the question of when the effort for such "diagnostic cleaning" is warranted. It is certainly useful in plants which do not have any other good data on oxide evolution available. This is, for example, in plants which have operated successfully for a long time, but supervision of the generator cooling system was not fully implemented and documented.

Total Flow/Pressure Differential Measurement

Most generators are equipped with instrumentation to measure total flow through the generator winding and pressure difference across the generator winding. Those generators which are not so equipped certainly should be. Such instrumentation provides reliable on-line monitoring of flow restrictions.

The flow measurement should reflect the actual water flow through the stator winding itself. The pressure difference must also be measured across the stator winding only. It has to be either a pressure meter measuring the pressure difference, or it can be two independent meters for absolute pressure. It is important that the connections for this measurement are actually at the stator inlet and stator outlet connections. Pressure meters at the pump give irrelevant numbers as such measurement includes filters, valves with variable settings etc.

Data can be collected in different kinds of ways: periodic measurement of the flow/pressure drop characteristics on the occasion of outages, or regular readings at given flow conditions.

Figure 2 displays the full pressure drop characteristics of a stator. For this, the flow was varied by reducing the flow stepwise with the pump outlet valve. It is obvious that this can only be done during an outage. During operation single points can be obtained (Figure 3).

Figure 4 displays the long-term trend of pressure drop readings at the given water flow. It can be seen that the direct readings of flow and pressure difference give a confusing picture as one influences the other. It is recommended to normalize the pressure difference to a reference flow rate, e.g. to nominal flow. This gives a much clearer picture. Of course, it is also possible to normalize

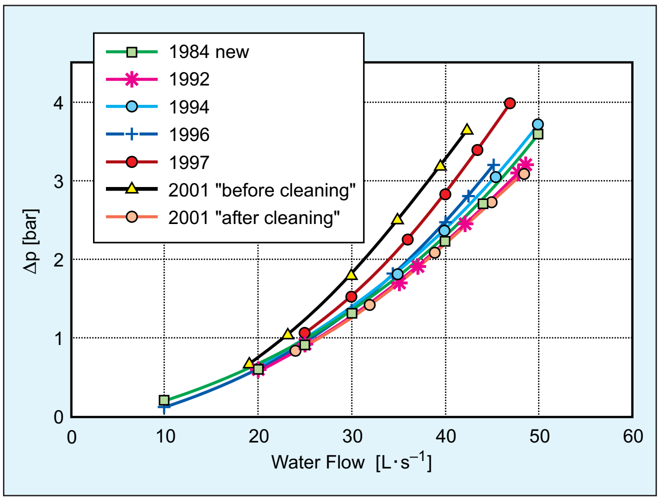

Figure 2:

Plant L: Stator flow/pressure drop characteristics as measured during outages.

Operating conditions between commissioning in 1984 and 1992 were stable. From 1992 until 2001 pressure drop slowly increased, thus indicating slow plugging in the system. Chemical cleaning in Aug 2001 restored conditions to "as new".

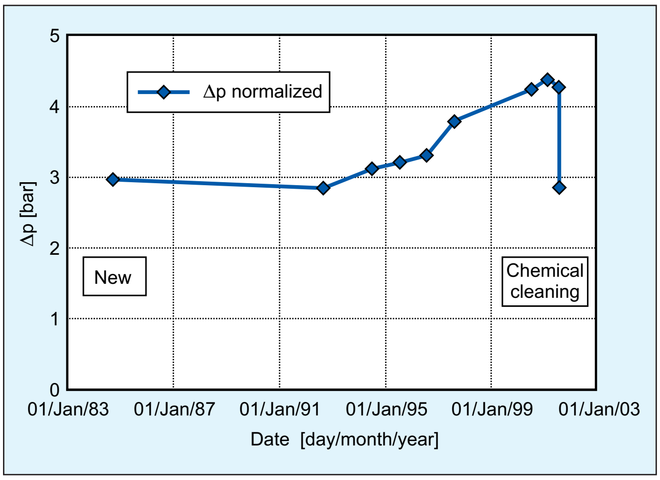

Figure 3:

Plant L: Long-term trend of stator pressure drop.

Pressure drop was measured at given flow conditions and then normalized to a reference flow (here 46 L · s^{-1}).

the flow to a reference pressure drop. Both of these normalizations are done by the well-known square dependence of pressure drop on flow.

Normalization of pressure drop (Δp) to standard flow rate (F) is shown in Eq. (1):

$$p_n = p \cdot \left(\frac{F_{ref}}{F}\right)^2 \qquad (1)$$

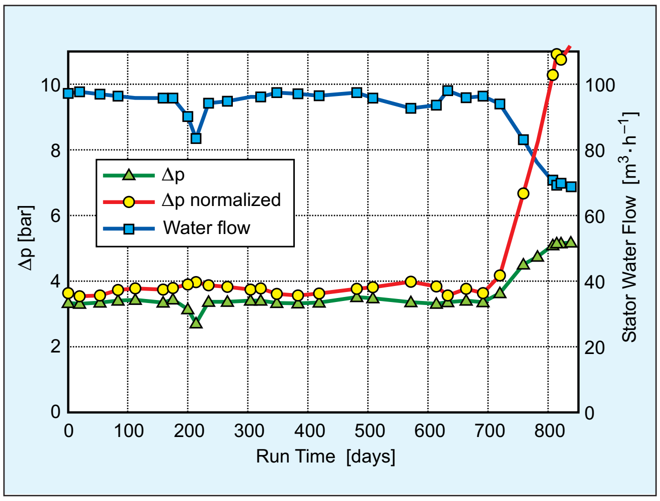

Figure 4:

Plant B2: Long-term trend of stator water flow and pressure drop.

The measured flow and pressure drop show a confusing picture. There are decreases in flow around day 200 and after day 700. When normalizing the pressure drop (here to 100 L · s^{-1}), it is seen that hydraulic conditions were stable up to day 700, and deteriorated afterwards (same event as in Figure 1).

where

p_n	Δp normalized to F_{ref}
p	Δp measured at F
F	measured flow rate
F_{ref}	reference flow rate

Individual Bar Flow Measurements

Because the stator works at high voltage, and the stator cooling water system is at ground voltage, the supply of water for every stator bar passes through an insulating water hose, in most cases made of polytetrafluorethylene (PTFE), e.g. Teflon™. There is also a corresponding water outlet hose. Depending on design, one water hose may supply just one bar, two or more bars in series, a group of bars in parallel, or another configuration of bars.

It is possible to perform flow measurements, using ultrasonic emitters with Doppler frequency detectors, which can be calibrated for flow velocity. Such Doppler flow measurement on individual stator bars, or on a group of bars, provides a more detailed picture of flow restrictions than the global measurement of the total flow through the stator winding (Figure 5).

Doppler flow measurements can be made only during shutdown, with the machine partly disassembled in order to gain access to the otherwise concealed water hoses.

For precise measurements it is quintessential to have very reproducible relations with regard to hose geometry, espe-

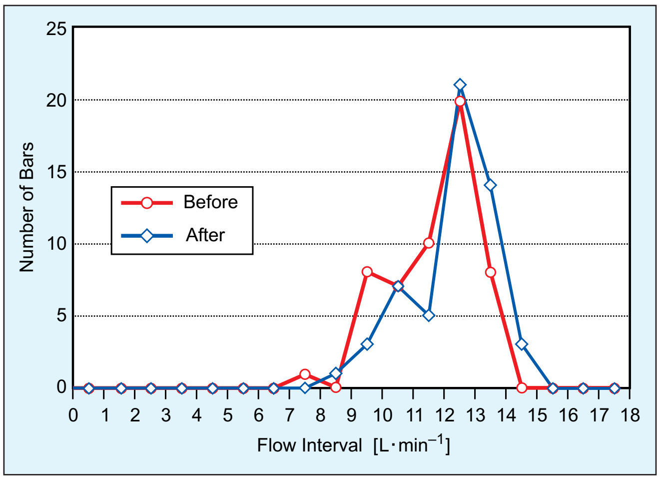

Figure 5:

Plant S3: Flow distribution in the stator bars before and after water flushing.

This example shows that water flow is moderately impaired and flushing did not have a significant effect.

cially the distance for relaxation of flow and turbulence up- and downstream of the instrument. While it is not too difficult to obtain reproducibility across the different hoses of a generator of ± 20 %, such high variations permit only the identification of severe flow reductions. Instruments, procedures and experienced personnel should be utilized in order to achieve a reproducibility of ± 5 % or better; ± 2 % is achievable.

When evaluating the individual bar flows, they have to be arranged into groups with comparable flow conditions. For example, the phase leads or the terminal collectors have different flow than the bulk of the stator bars.

Temperature Measurements On-line

During operation, the generator heats up to its normal operating temperature. The rise of cooling water temperature across the stator (above this normal value) can serve as a useful measure for impairment of cooling water flow.

The quantity of heat transport in the water is proportional to the quantity of water multiplied by its specific heat capacity ($C_P = 4.2\ J \cdot g^{-1} \cdot K^{-1}$). At a given heat production of the generator, the temperature rise is therefore indirectly proportional to the water flow. If flow restrictions reduce water flow, the water outlet temperatures will increase.

Variations in cooling water flow, hence also in temperature rise, are also caused by variations in pump output or system flow control valve settings. Such effects have to be taken into account when interpreting data.

The temperature rise is also governed by variation in the heat losses of the generator, which are dependent on generator load. The heat losses follow to a large part Ohm's law (applicable for pure resistance systems), which indicates that heat production is proportional to the square of the current. At a given water flow, the heat-up of the bars is therefore approximately a square function of the generator current, which is proportional to the MVA generator load. Some of the heat is also dissipated by gas-side cooling. In practice it was found that a second order polynomial fit with a linear component gives good results.

Normalization of temperature rise (T) to a reference generator load (L) is shown in Eq. (2):

$$T_n = T \cdot \left[a \cdot \left(\frac{L_{ref}}{L} \right)^2 + (1 - a) \cdot \left(\frac{L_{ref}}{L} \right) \right] \tag{2}$$

where

T_n	T (above inlet) normalized to L_{ref}
T	T (above inlet) measured at L
L	measured MVA
L_{ref}	reference MVA
a	plant specific coefficient

T (°C or °F) is always defined as the temperature rise above the inlet water temperature. A precise water inlet temperature measurement is therefore required. If this feature is not available, it should be retrofitted.

The plant specific coefficient "a" can be determined by comparing temperature readings made at different load levels within a short period, such as on one day. It has to be taken into account that this calculation is approximate and should be used in a plant-specific narrow load range only. In the plants investigated so far, the formula was found to give an error of less than 1 °C between 80 % and 100 % load. Coefficients are usually 0.8–1.0, but 0.6 was also found in a particular case.

In many plants it is not the temperatures that are monitored, but temperature differentials, e.g. "Delta T max" (temperature difference between the hottest and the coldest bar in a group), or "deviation from average". Because the normalization factor (T_n/T) is the same for all bars, the temperature differentials can also be corrected by multiplying by the same normalization factor.

Due to the different influence of gas-side cooling, the coefficient may be different for water outlet temperatures and for slot temperatures.

Global system temperatures A temperature indication at the inlet collector and one at the outlet collector does not provide very useful information for our purposes. The global temperature rise is a direct function of the generator heat loss (that is, it is dependent on the MVA) and the water flow, with a minor influence of gas-side cooling.

Thus variations in the global system temperatures do not provide much useful specific information.

Temperatures at the water outlet Teflon hoses Many generators are equipped with resistance temperature devices (RTD) or thermocouple (TC) elements fixed to the ends of the outlet Teflon hoses. Depending on their thermal contact to the hose they largely reflect the water temperature in the hose. There may also be a slight influence of the temperature of the hydrogen gas which is circulated on the other side of the Teflon hoses. This cooling by the hydrogen may be asymmetrical around the stator; therefore slightly different RTD temperatures do not necessarily also mean different water temperatures. In the extreme case of a completely plugged bar, the RTD takes up the hydrogen temperature and thus may misleadingly even indicate a lower than average bar temperature.

Depending on the hydraulic design of the stator cooling, such a Teflon hose may represent the water coming from just one individual bar, or from several bars in series or in parallel. This has to be taken into consideration when evaluating the data. Bars which have a different hydraulic length have different water flow, thus different outlet water temperatures. In generators equipped with such bars, they have to be considered individually. An example is given in Figure 6.

There is the question of how responsive individual bar outlet water temperatures are to localized heating. This depends on the design of the bar and especially on the number of conductors in a bar. In most cases one completely plugged conductor does not result in heating the water significantly above the bulk temperature, but nevertheless it can already cause a localized hot spot. An example is given in Figure 7 [12]. Because bar outlet water temperatures are related to the individual bar's water flow, it can be assumed that the response of bar outlet water temperatures may have a similar meaningfulness to single bar Doppler flow measurements.

It is recommended to perform these temperature measurements regularly, well before any problems have come up. This data should already have been taken and recorded as a baseline at the initial commissioning of the machine. With such procedures, the "fingerprint" of each point is known and developments can be identified with enhanced sensitivity.

Of special interest here is the use of advanced pattern recognition monitoring (APR). This method analyses the actual operating data by comparison to the expected behaviour, which is derived from historical data. Key features are a data compilation algorithm for the historical data, and a prediction algorithm for the actual operating condition. An APR module can be linked to the plant's data acquisition system [6].

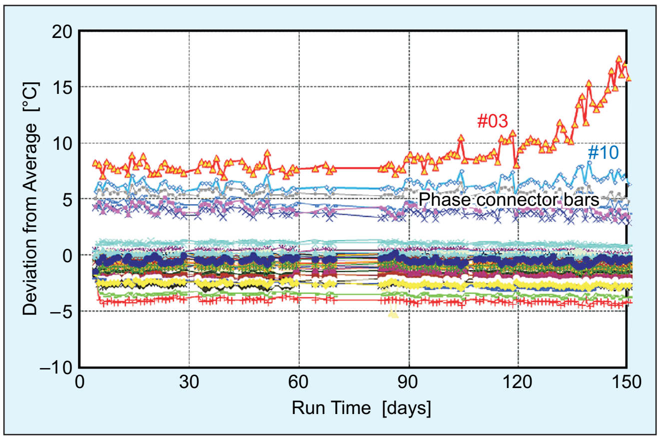

Figure 6:

Plant C1: Normalized Teflon hose temperatures.

The temperature distribution shows two distinct groups and some outliers. The compact group around 0 °C and below represents the bulk of the bars, their deviation being within the normal range. The second group around 5 °C includes bars in series with phase connectors which are expected by design to be 5 °C higher than the bulk. No. 10 is a bit higher than the others, and No. 3 has a higher temperature from the beginning, with a strong increase after day 120, thus necessitating a chemical cleaning.

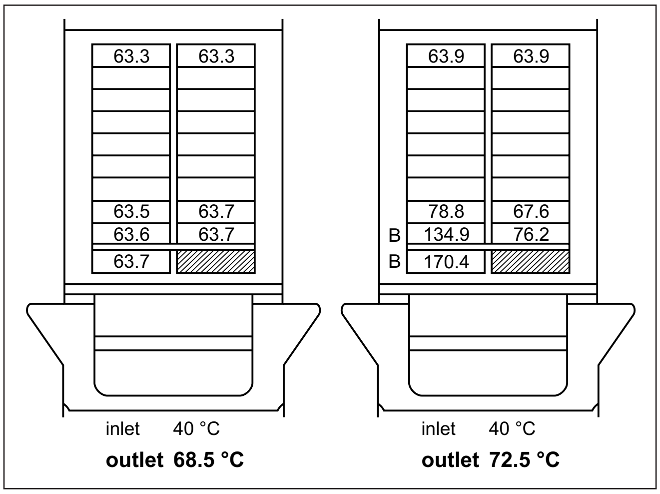

Figure 7:

Calculated hot spot temperatures in the top bar of a 540 MW generator at full load [12]. Indicated below are the water temperatures at the inlet and the outlet water collector of the generator. B indicates blocked hollow conductors. The bar consists of 19 strands, all of them hollow, and a dummy strip at the endings. Temperatures are given in °C. It is seen that 2 blocked strands increase the bar outlet temperature by only 4 °C, but the local hot spot is already 170 °C.

Temperatures in the stator slots Many generators are equipped with TC (or RTD) elements fixed in the stator slots. Depending on the design of the stator slots, such temperatures represent a mix of the temperatures of two or more bars. This has to be taken into consideration when evaluating the data.

The stator slot data and their limitations are quite comparable to the data from the Teflon hoses. While it is harder with the slot measurement to identify the affected bar, slot measurements are considered to be more responsive to localized heating, especially in a single pass design.

Visual Inspections

A visual inspection provides first-hand information on flow restrictions. Because of the narrow size of the hollow conductors, such visual inspections will be limited to the inlet and outlet of the hollow conductors, already providing most of the useful information. The inside of the hollow conductors, especially the flow transitions at the Roebel transpositions, still remains unseen however. Visual inspections can only be performed during shutdown and may require considerable dismantling of the generator.

Direct visual inspection of the stator bars This inspection provides very valuable information about the conditions at the hollow conductor ends. Deposits can be seen and their thickness can be estimated or even measured. Their compactness can be tested with a needle or other tools. Analysis of deposit samples can help identify the probable origin and cause of the deposit. It is further useful to identify the best method for cleaning. Note that the specific design of a generator and its parts has an important influence on the accessibility for direct visual inspections.

Videoprobe inspections of the stator bars With videoprobes all parts of the hollow conductor ends can be inspected. The videoprobe can be introduced either via the bore of the water chambers, or from the other end of the Teflon hose through this hose. A videoprobe head with movable direction is useful for pointing to all parts of the water chamber and at all hollow conductor ends.

The pictures can be recorded either as single shots or as a movie. Single shots provide the best picture quality. Views from different angles may help prevent optical illusions, e.g. white deposits which are really only reflecting traces of water etc. Movie recordings on the other hand give a good 3-dimensional impression. The movement of the shadows allows quick identification of the depth of deposits. Figure 8 and Figure 9 give examples of single shots.

Visual inspection of the stator bars, combined with mechanical methods When the water chambers are open, it is prudent to combine the visual inspection of the hollow conductor endings with mechanical examination methods.

Most useful is single hollow conductor flow testing. For this, a small supply hose with pressurized air (or nitrogen) is equipped with a rubber nozzle at its end, such that it fits into an individual hollow conductor's end opening. When pressurized air is applied to a hollow conductor's opening, it is necessary to check if air is coming out at the other end. This can be done by pulling a thin balloon over the bore of the opposite water chamber. If the balloon shows signs of being filled, then the hollow conductor has an open passage. With some refinement of equipment, even some quantification of the flow can be obtained.

Such methods may seem to be a bit laborious, but they are the only means of providing direct information on the cooling condition of individual hollow conductors.

Figure 10 shows the result of such a test. Single bar flow measurements indicated severe flow restrictions. It was therefore expected to find many plugged hollow conductors. A surprise was, however, that even the bars which had quite normal single bar flow also had 10–25 % of their hollow conductors plugged.

Figure 8:
Hollow conductors with oxide plugging.

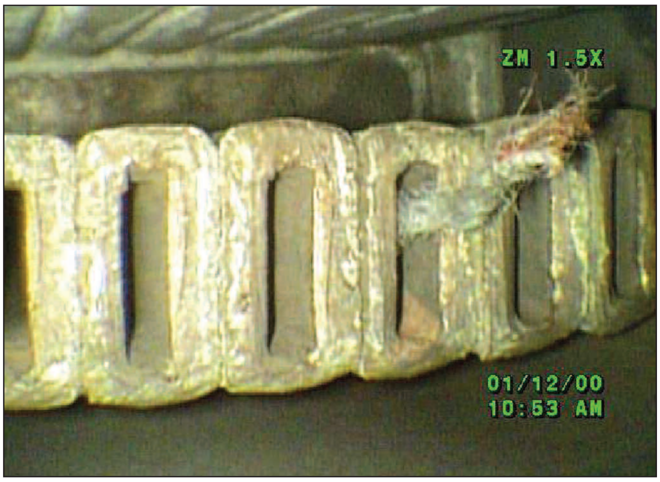

Figure 9:
Hollow conductors with debris.

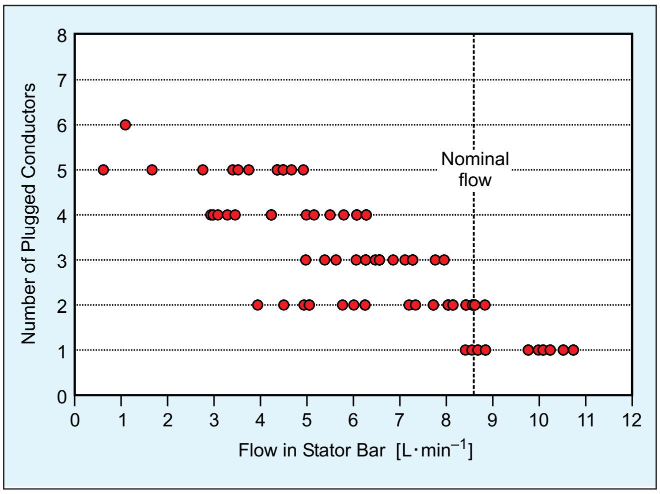

Figure 10:

Plant P3: Statistics on plugged hollow conductors before cleaning.

Horizontal axis: Results of Doppler flow measurements: water flow at the outlet Teflon hose of each of the stator bars. Nominal flow of a clean bar would be 8.6 $L \cdot min^{-1}$ in this generator. The flow is severely impaired in the majority of the bars. Because all bars are hydraulically in parallel, the cleaner bars receive an above-normal flow.

Vertical axis: Results of single hollow conductor flow testing: number of totally plugged hollow conductors of each bar. Each bar has 8 hollow conductors. Up to 6 conductors were completely plugged.

Even the bars with nominal flow or higher had some completely plugged hollow conductors. All plugs were subsequently opened by mechanical cleaning.

This demonstrates that the visual inspection, combined with mechanical methods like single hollow conductor flow testing, provides the best results.

There are many possible variations of this method. Pinpoint size flow detectors (self-heated temperature elements that cool off with air flow), feathers or foam could for example serve to indicate air flow at a conductor outlet.

It is evident that the effort required for such methods may be very demanding for water chambers that do not permit straight access to their conductor endings.

DC High-Potential (Hipot) Test Off-line

The leakage current of the stator can give an indication of copper plate-out in the system. A practical measure is obtained by measuring the resistance of the stator towards ground when the plant is shut down. This resistance depends for one thing on the resistance across the Teflon hoses, but also on the resistance of the water inside the Teflon hoses. The resistance of the water is much smaller than the resistance of the Teflon hose, which means measurement of the total resistance is normally dominated by the water. It is therefore best if the generator is drained and dried for the resistance measurement. But even when the generator is not drained, the data is useful. It just has to be considered that the resistance of the water depends on its purity (which may be degraded during shutdown) as well as on the water temperature.

The data should be used comparatively to earlier measurements. This means that regular measurements are necessary in order to have a good database.

Decreasing resistivity can mean conductive deposits on the Teflon hoses. They are an indication of copper plate-out in the system, either electrochemical plate-out or deposit of metallic copper particles (Figure 11). High leakage currents during operation may lead to serious damage of equipment. Deposits of copper particles in the system may lead to hard-to-remove flow restrictions.

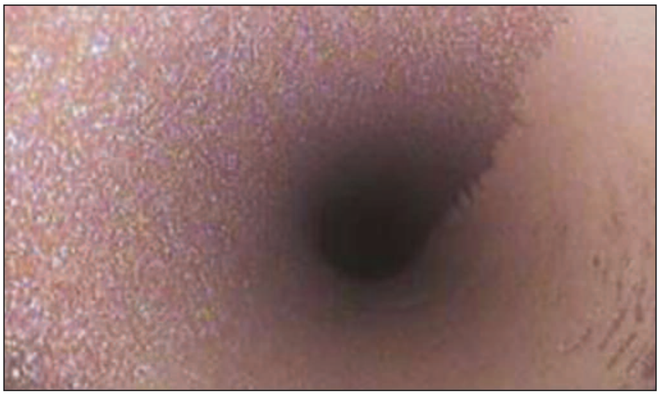

Figure 11:

Videoscopic image of deposits in a Teflon hose of the cooling water supply to the stator.

COMPARISON AND ASSESSMENT OF THESE METHODS

Regular review of operating parameters is a simple way of gaining information and is practically free of charge if considered to be a part of normal housekeeping. It does not provide direct information on clogging conditions in the generator, but gives a good indication with regard to risk factors.

Assessing the frequency of strainer or filter clogging gives a direct indication of oxide migration in the system, which probably also affects oxide deposition in the generator.

Diagnostic cleaning gives integral information on the oxide deposit over a longer time period. It requires additional effort, but also provides the additional benefit of having the generator clean again. It is especially useful for generators of a higher operating age.

Total flow and pressure drop measurement is done on-line as well as off-line with simple instruments. It gives a reliable indication of the global plugging conditions of the generator. Data should be normalized either to a standard flow or to a standard pressure drop. It is however not sensitive to conditions in an individual bar.

Individual bar flow measurements give a good indication of the flow integral of all hollow conductors in an individual bar. This can be done only at shutdown and requires entrance of personnel to the inside of the generator. It has great value in displaying and localizing deteriorated flow, however it does not give conclusive indication of whether certain hollow conductors are plugged or not. Even with bars showing high flow measurements, it is still possible that one or more individual conductors or strands are already plugged.

Temperatures at bar water outlets or in the individual slots provide information that is basically comparable to the flow measurements, but more precise. This data can only be acquired on-line, i.e. while the generator is running.

Visual inspection gives some of the best and in any case the most immediate information. However it may require considerable effort to gain access to the components and can only be done at shutdown. Visual inspections are therefore a good complement to the other methods, especially where there are indications of severe plugging that need to be verified or even followed up by localized manual cleaning.

The information obtained is most useful when several of the above-mentioned methods are used in combination. The specific design of a generator and its component parts has an important influence on the accessibility for detecting flow restrictions. Therefore not necessarily all the listed options may be feasible in a particular case.

This assessment is summarized in Table 1.

RECOMMENDATIONS

A proactive approach to detecting flow restrictions should be taken. This provides an earlier warning for upcoming problems. Corrective actions can be planned in advance, thus reducing the risk of unplanned maintenance downtime, expensive rewinds or even component failure. Managing flow restrictions at an early stage reduces the risk of severe plugging of conductors that may be very difficult to remove later on.

Operating parameters and the occurrence of strainer/filter clogging should be frequently assessed (e.g. every month). Monitoring of system copper release by analysis of the spent ion exchange resin is recommended. Installation of on-line oxygen monitoring has to be considered on a case by case basis; it is not always practical.

Diagnostic cleaning is recommended for plants of an advanced operating age.

Continuous individual bar temperature measurements (slots and/or outlet water hoses) are recommended.

Indication of total stator water flow and pressure drop should be available and the data evaluated regularly (e.g. monthly and more frequently after transients).

Individual bar flow measurements should be made proactively at regular intervals as well as when other parameters suggest the likelihood of plugging.

Visual inspections provide the most immediate information and should be made whenever there is a good and easy opportunity to do so. If severe plugging is suspected, larger efforts for such inspections are usually warranted. Visual inspections, supported by mechanical methods, provide the most conclusive information on the plugging conditions of a generator. They may however not always be fully feasible with reasonable effort.

If any such investigations would interfere with normal operating conditions (e.g. allowing air to enter a low-oxygen system), the benefit of the investigation has to be considered with regard to the possibility of intensifying any plugging.

Required minimum stationary plant instrumentation:

- indication of total stator water flow and pressure drop
- indication of individual bar temperatures (slots and/or outlet water hoses)
- on-line oxygen monitor (optional, plant specific)

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Method	On-/Off-Line		Benefit				Price		
	off-line	on-line	some	fair	good	excellent	low	medium	high
Assessment of									
operating parameters	x	x		x				x	
operating history	x	x	x				x		
system water chemistry	x	x			x		x		
Strainer and filter clogging history	x	x		x			x		
Diagnostic cleaning	x	x		x				x	
Total flow / pressure drop measurement (*)	x	x			x		x		
Individual bar flow measurement	x				x				x
Temperature measurements on-line									
global system temperatures (*)		x		x			x		
water outlet Teflon hose temperatures (*)		x				x		x	
stator slot temperatures (*)		x				x		x	
Visual inspections									
cooling water system components	x	(x)	x				x		
stator bars	x					x			x
stator bars, combined with mechanical methods	x					xx			x
DC High-Potential Test		x	x					x	

Table 1:

Comparison of methods to detect flow restrictions.

"On-/off-line" specifies under which condition the method is available. "Benefit" is understood to be the degree of relevant information derived on the subject. "Price" indicates the material and/or labour efforts required. The degree of Benefit and Price may vary in specific cases.

(*) requires matching stationary plant instrumentation

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